# 2006 NASA Earth Science Technology Conference

# Mars Technology Program (MTP) Communications and Tracking Technologies for Mars Exploration


**Technical Lead:** ***Dimitrios Antsos***

**Jet Propulsion Laboratory**


***June 27, 2006***

# Objectives

- The future of Mars Exploration will see an unprecedented increase in the volume of data generated by an increasingly capable host of science instruments on various rovers, aerobots, orbiters and eventually humans.
- To return these large volumes of data to Earth, communications links with data-rates in the multiple Megabits-per-second will be required.
- The *Telecommunications and Tracking* element of the MTP Base Technology Program is developing critical, enabling technology components and products that will dramatically increase the aggregate data return from Mars to Earth, while lowering implementation costs.

# Approaches

## The 4 Forms of the *Friis Free-Space Transmission Formula*

$$\frac{P_R}{P_T} = \frac{A_R A_T}{c^2 L^2} f^2 = G_R \left( \frac{c}{4\pi fL} \right)^2 G_T = A_R \frac{G_T}{4\pi L^2} = \frac{G_R}{4\pi L^2} A_T$$

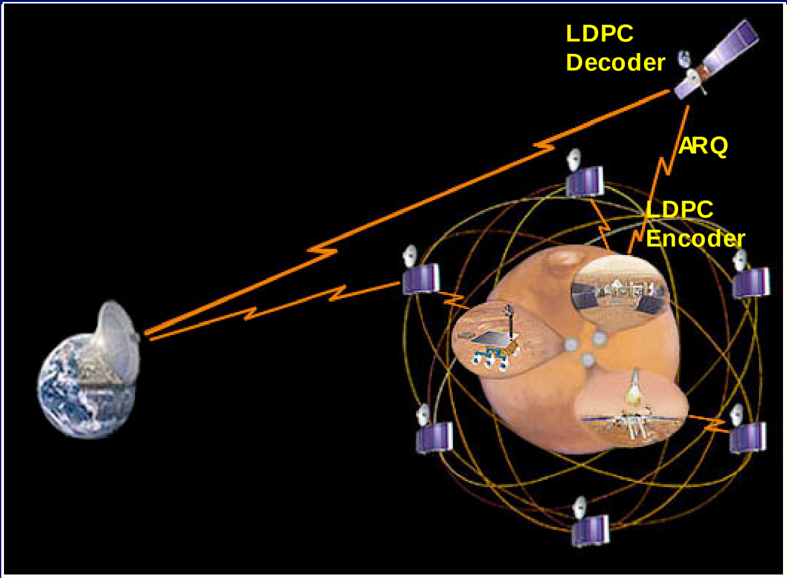
Can increase aggregate data return by:

- Increasing the data-rate for a given $P_R$ (Coding, Reducing “Margin”)
- Increasing the carrier frequency, if both antennas are “constant area”
- Increasing the gain of one or both antennas (Agile beam, Multi-path Mitigation)
- Increasing $P_T$ for a given size, mass, power and/or cost

**Objective:** *Develop communications technology for future Mars missions that will dramatically improve link capabilities and performance with higher data rates and lower costs.*

| Technology | Task | Description | Year 1 $K | Year 2 $K | Year 3 $K | Total $K | Tech $K |
|---|---|---|---|---|---|---|---|
| **Coding/ Protocols** | 1. Coding for High Data-Rate Links | LDPC encoder/decoder for proximity links | 347 | 338 | 210 | 895 | 2256 |
| | 2. Autonomous Radio for Proximity Links | Reduced link margins with autonomous operation | 258 | 281 | 352 | 891 | |
| | 3. Adaptive Data Rates for ELECTRA | Increase aggregate data return by increasing data rate during a pass, when possible | 220 | 210 | 40 | 470 | |
| **Optical Comm** | 4. Large Fresnel Lenses as Ground Receivers | Ground optical receivers for future optical communications | 240 | 250 | 260 | 750 | 750 |
| **Antennas** | 5. X-band Agile Beam Transmitter | Agile beam array compatible with Electra | 287 | 262 | 287 | 836 | 2415 |
| | 6. Fast & Accurate EM Modeling | Accurately predict spacecraft/antenna EM performance | 250 | 250 | | 500 | |
| | 7. UHF/X-band Proximity Link Antennas | Lander and orbiter simultaneous UHF/X-band antennas | 254 | 395 | 430 | 1079 | |
| **Transceivers** | 8. Mars Proximity Microtransceiver | Miniaturized UHF transceiver compatible with Electra | 296 | 296 | 291 | 883 | 1724 |
| | 9. Reprogrammable Transceiver Modem | Reprogrammable transceiver modem with reduced mass and power | 422 | | | 422 | |
| | 10. X-band Applique for ELECTRA | X-band transceiver applique compatible with Electra | 226 | 193 | | 419 | |

# *1. Coding for High Data Rate Links* (Increase Data-Rate for a given $P_R$)




**Objectives:**

- Develop an LDPC code suitable for proximity links using ARQ protocols. Analyze and simulate its performance
- Define the architecture for the implementation of the encoder and the parallel decoder
- Develop encoder in FPGA
- Develop parallel decoder at 5 Mbps in FPGA and benchmark speed and performance
- Integrate encoder and decoder into Electra radio
- Define a suitable ARQ protocol integrated with the code. Analyze/simulate its performance

**PI:** **Dr. Christopher R. Jones**
Phone: 818-354-4287
Email: Fabrizio.Pollara@jpl.nasa.gov
**Co-I:** **Dr. Dariush Divsalar**
Phone: 818-393-5138
Email: Dariush.Divsalar@jpl.nasa.gov
**Co-I:** **Dr. Samuel Dolinar**
Phone: 818-354-7403
Email: Samuel.J.Dolinar-Jr@jpl.nasa.gov
**Co-I:** **Dr. Norman Lay**
Phone: 818-393-4880
Email: Norman.E.Lay@jpl.nasa.gov
**Co-I:** **Prof. William Ryan**
Phone: 520-621-8690
Email: ryan@ece.arizona.edu

**Participating Organizations:** University of Arizona

## Key Milestones:

**FY05** Proximity coding system design and analysis

On-board LDPC encoder module prototype

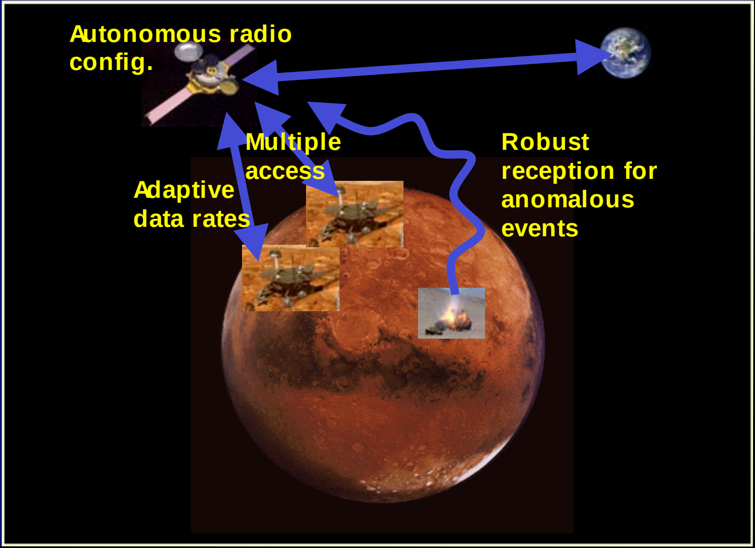
**FY06** On-board decoder prototype

**FY07** Integrate encoder and decoder into Electra. Demonstrate full system

# *Coding for High Data Rate Links*
# Significant Accomplishments and Current Status

- *Low Density Parity Check codes (LDPC) using ARQ (Automatic Retransmit Requests) designed and tested.*
- *HDL implementations of selected LDPC codes tested and verified.*
- *Hardware LDPC decoder implemented in FPGA.*
- *Electra Radio* Baseband Processor Module *in Electra Testbed modified to provide hardware interface, allowing for end-to-end encoder/decoder bit-error-rate tests.*
- *Successful Bit Error-Rate tests performed using pre-encoded LDPC sequences.*

## *2. Autonomous Radio for Proximity Links* (Increase Data-Rate for a given $P_R$)




**Objectives:**

- **Reduce observed margin by**
  - **Implementing adaptive data rate protocol**
  - **Using multiple resolution modulation.**
- **Develop robust multiple access strategy for proximity links.**
- **Make radio operate autonomously, to identify incoming signal and process it appropriately.**
- **Demonstrate autonomous operation on Electra engineering model or software implementation of Electra.**

**PI:** **Dr. Jon Hamkins**
Phone: 818-354-4764
Email: Jon.Hamkins@jpl.nasa.gov
**Co-I:** **Dr. Dariush Divsalar**
Phone: 818-393-5138
Email: Dariush.Divsalar@jpl.nasa.gov
**Co-I:** **Dr. Edgar Satorius**
Phone: 818-354-5790
Email: Edgar.Satorius@jpl.nasa.gov
**Co-I:** **Dr. Samuel Dolinar**
Phone: 818-354-7403
Email: Samuel.J.Dolinar-Jr@jpl.nasa.gov
**Co-I:** **Dr. Kenneth Andrews**
Phone: 818-354-5865
Email: Kenneth.Andrews@jpl.nasa.gov
**Co-I:** **Prof. Wayne Stark**
Phone: 734-763-0390
Email: stark@eecs.umich.edu

**Participating Organizations:** University of Michigan

## Key Milestones:

**FY05** Develop multiple resolution modulation techniques and adaptive data rate protocols

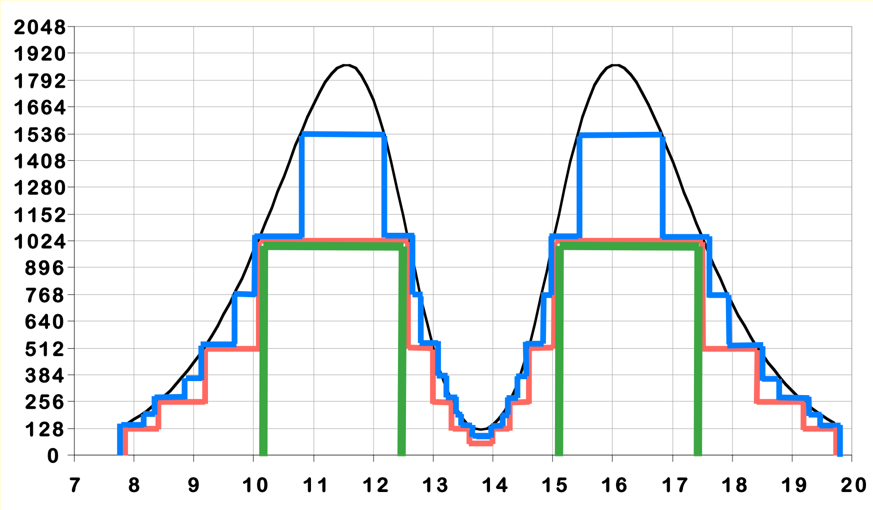
**FY06** Demonstrate autonomous algorithms on Electra-like platform

**FY07** Develop multiple access strategies suitable for proximity links

# *Autonomous Radio for Proximity Links*
# Significant Accomplishments and Current Status

- *Developed algorithms to estimate and auto-configure channel state, using maximum likelihood solutions or approximations:*
  - *Modulation type (BPSK, QPSK, M-PSK) classification*
  - *Frequency-offset estimation*
  - *Data format (NRZ/Manchester) classification*
  - *Carrier phase estimation*
  - *Modulation index (suppressed/residual carrier) estimation*
  - *Data rate, SNR, coarse symbol-timing estimation*
  - *Fine symbol timing estimation*
  - *Automatic configuration of loop bandwidth*
- *Fixed-point implementations of two of the above algorithms have been coded and verified.*
- Modulation Detection *algorithm successfully demonstrated in Electra Testbed.*
- *Task on 6-month "hiatus" due to cut in 2006 MTP funding.*

## *3. Electra Adaptive Data Rates* (Increase Data-Rate for a given $P_R$)




### Objectives:

- **To increase Mars relay data volume return by demonstrating an adaptive data rate capability in which the relay data rate is varied according to real-time measurements of the channel characteristics**
- **Develop, implement, and demonstrate an Adaptive Rate function on the Electra Prototype Radios**

**Task Manager:**
Caroline Racho
Phone: 818-354-6481
Email: caroline.racho@jpl.nasa.gov

**Participating Organizations:**
JPL/CMCEC

**Facilities:** EPP testbeds

### Key Milestones:

**FY04** Develop algorithm and determine implementation

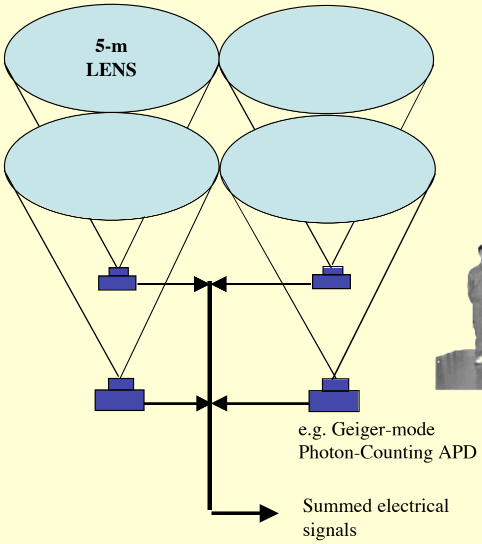
**FY05** Demonstrate SNR estimator on Electra Prototype Hardware

**FY06** Demonstrate Adaptive Rate Capability on MRO Electra Prototype Hardware

# *Electra Adaptive Data Rates*
# Significant Accomplishments and Current Status

- *Developed, Built and Tested Electra Prototype Adaptive Data Rate Testbed, including Hardware Channel Emulator*
- *Implemented Channel Estimator and Data-Rate Decision Module in Electra* Baseband Processor Module
- *Implemented Electra Proximity-One Comm Change Function in Software*
- *Successfully demonstrated full operation on the Electra Testbed, and "infused" into MSL / MRO missions.*

## *4. Large Fresnel Lenses as Ground Receivers* (Increase Carrier Frequency)




**3m x 5m Fresnel lens**

## Objectives:

- Proof-of-concept demonstration of large-diameter (~ 2-m) refractive Fresnel lenses producing sub-mm focal spot size at 1064-nm
- Demonstration of functionality of these lenses as viable Optical Communications ground receivers under the field environment and at small (< 3°) Sun angles
- Demonstration of cost effective extension of the aperture diameter to 5-meters and larger, and low-cost reproduction
- Side-by-side comparison of these receivers with conventional optical comm receivers, in the field

**PI: Hamid Hemmati (JPL)**
Phone: 818-354-4960
Email: hamid.hemmati@jpl.nasa.gov
**Co-I: Sham Dixit (LLNL)**
Phone: 925-423-7321
Email: dixit1@llnl.gov

**Participating Organizations:**
JPL, Lawrence Livermore National Lab (LLNL), Texas A&M U.

**Facilities:**
JPL's Optical Communications Lab.
LLNL's Large Optics Manufacturing Lab.

## Key Milestones:

**FY05 -** Development and testing of custom large diameter (1-2-m) Fresnel lenses.

**FY06 -** Development and testing of large diameter (> 1.5-m) optical comm ground receiver telescopes utilizing Fresnel lenses

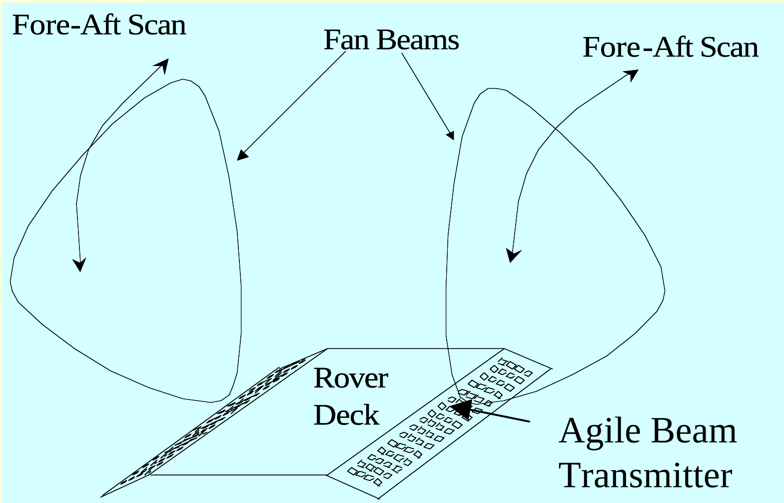
**FY07 -** Field testing of the receivers and side-by-side comparison in performance with a 1-m conventional telescope

# *Large Fresnel Lenses as Ground Receivers*

# Significant Accomplishments and Current Status

- *Task cancelled effective 5/06 due to cut in 2006 MTP funding.*
- *Characterized three large off-the-shelf lenses with two different techniques. The 80% encircled energy diameter exceeds 3 mm in all cases (3 to 5 mm).*
  - *Unacceptably large spot sizes (not meeting requirements). Require custom-made lenses designed for the wavelength of interest*
- *Breault Research Org. performed a detailed stray-light analysis for Fresnel lenses*
  - *Stray-light requirement not met below 13°, resulting in 4 months of outage for a typical 2-year Mars mission*
- *Lawrence Livermore Lab diamond-turned a custom 0.6-m lens (designed by ORA) as a precursor to fabricating a 2-m diameter lens.*
  - *The lens was partially characterized, measured a spot size of ~ 0.4 mm*
- *RHK Inc. (Japan) fabricated a 2-meter 1064-nm lens*
  - *The lens was partially characterized. Grooves and planes do not quite match.*
- *Integrated an Active Optics system for correcting lens-induced spherical aberrations and improving the focus spot size.*
  - *Preliminary results indicate partial correction. Wavefront sensor malfunctions due to scattering centers generated by the grooves.*
- *Procured and configured a 1.5-meter Beam Expander that will provide a 1.5 meter diameter collimated beam, for Fresnel lens testing.*

## 5. X-band Agile Beam Transmitter (Increase Antenna Gain)




## Objectives:

- **Enable low cost high rate data transfer (100X relative to omni-directional antenna) from landed assets and airborne vehicles on Mars to a low orbiting satellite for relay to Earth by developing a simple low cost X-band (8.4 GHz) agile beam transmitter with integrated antenna.**
- **It is intended that this transmitter be compatible with the X-band receive option of the Electra payload.**

**PI: Dr. Ronald J. Pogorzelski**
Phone: (818)354-3835
Email: pogo@jpl.nasa.gov
**Co-I: Dr. Dimitrios Antsos**
Phone: (818)354-6343
Email: Dimitrios.Antsos@jpl.nasa.gov
**Co-I: Prof. L. Wilson Pearson**
Phone: (864)656-3946
Email: pearson@ces.clemson.edu

**Participating Organizations:**
JPL, Clemson University

**Facilities:**
JPL Mesa Antenna Measurement Facility
JPL Hybrid Circuits Laboratory

**Key Milestones:**

**FY05** Oscillator Development Complete
Radiating Element Design Complete

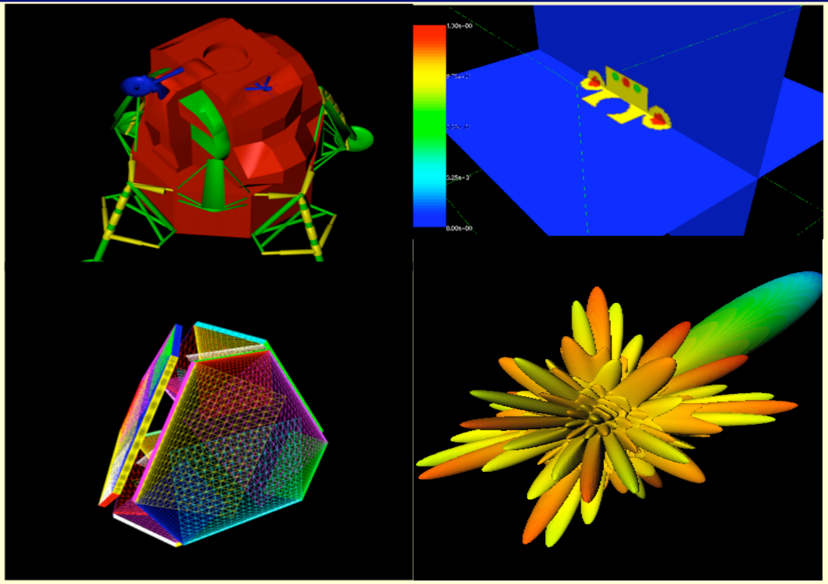
**FY06** X-band Array Design Complete
Small Array Demonstration
X-band Array Fabrication Complete

**FY07** Antenna Range Testing Complete
Data Transmission Test
Agile Beam Transmitter Demonstration

# *X-band Agile Beam Transmitter*
# Significant Accomplishments and Current Status

- *Custom oscillators, optimized for injection locking range and high-efficiency designed, built and tested.*
- *Modulation network and 3-element microstrip Yagi radiating aperture designed, breadboarded and tested.*
- *Breadboarded and tested Phase Calibration unit*
- *7-element linear Coupled-Oscillator Transmit Array currently in fabrication.*
- *21-element linear Coupled-Oscillator Transmit Array currently in final design.*

## *6. Fast and Accurate EM Modeling* (Increase Antenna Gain)



### Objectives:

•This effort will produce a simulation of the near and far-fields (including multi-path and impedance behavior) in antenna-spacecraft structures. This is based on the fast and accurate algorithms introduced recently at Caltech. The work will result in algorithms for multi-material electromagnetic solvers.

•The predictive capabilities of these solvers will be validated in JPL's antenna measurement facilities of antenna-spacecraft mockups.

**PI:** **Oscar Bruno**
Phone: 626-395-2814
Email: bruno@acm.caltech.edu

**Co-I:** **Vaughn Cable**
Phone: 818-354-2196
Email: vaughn.p.cable@jpl.nasa.gov

**Participating Organizations:**

California Institute of Technology, JPL

**Facilities:** 256 Processor Pent IV Xeon Cluster

### Key Milestones:

**FY05** Surface/volumetric CEM solver completed

Integration of geometry capability & CEM solver completed

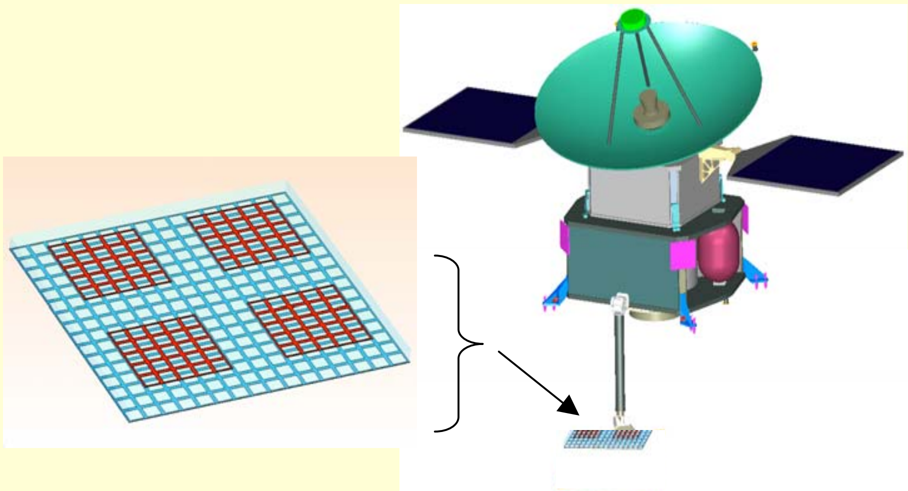
**FY06** Antenna range measurements of new physical test models.

Analysis & comparison of predicted pattern for MER CEM model completed.

# *Fast and Accurate Electromagnetic (EM) Modeling*
# Significant Accomplishments and Current Status

- *Caltech's "full-wave" EM modeling methods are based on integral-equation formulations of Maxwell's equations with the following new properties:*
  - *Acceleration strategies leading to much reduced operation counts*
  - *Super-algebraic convergence*
  - *High-order integration*
  - *Fast Fourier Transforms*
  - *Highly accurate high-frequency algorithms*
  - *Accurate treatment of corners and edges*
- *High-singularity (e.g. sharp edges and thin wires) EM algorithms designed and verified (order of N*log(N) convergence demonstrated!!)*
- *Validated against measurements from physical models*

## *7. UHF/X-band Proximity Link Antenna* (Increase Antenna Gain)



### Objectives:

- Design vitreous, or glass-like, antenna designs at UHF that allow X-band signals to pass through unimpeded
- Design both Lander and Orbiter UHF antennas and build and test them with respect to their relative vehicle platforms
- The purpose of this project is to support technologies for low cost UHF/X-band relay links between a Lander and orbiter

**PI:** **Anthony Jensen**
Phone: 303-533-7453
Email: ajensen@ball.com

**Participating Organizations:**

Ball Aerospace & Technologies Corp.

**Facilities:**

Ball, Antenna Ranges and Labs

### Key Milestones:

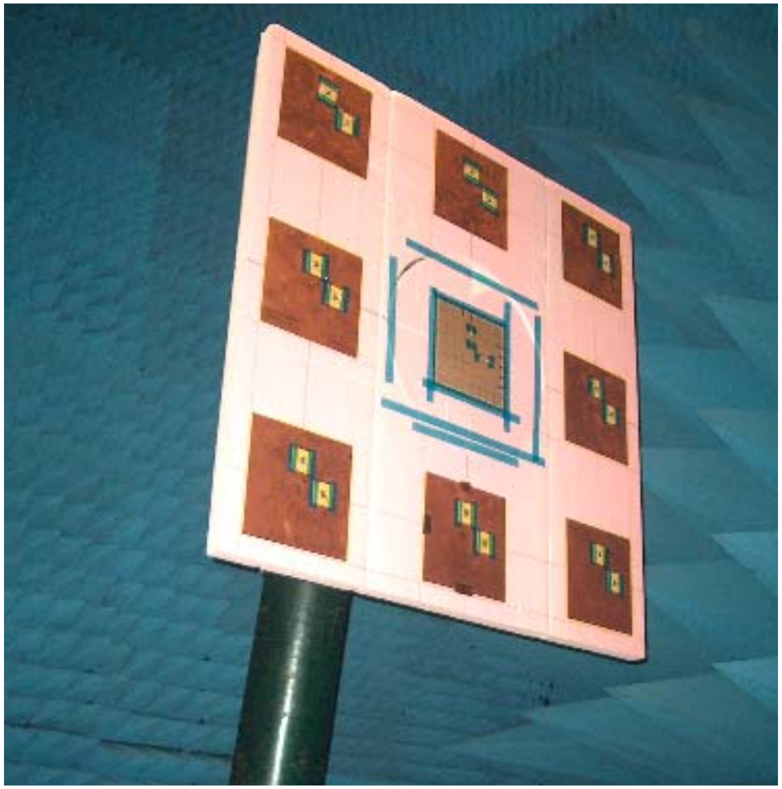
**FY05** Vitreous structure characteristics report, Orbiter element design, Lander element design, breadboard build and test of each

**FY06** Build and test prototype lander antenna and orbiter antenna array, Representative model build of Lander and Orbiter

**FY07** Antenna testing on relative platforms, Environmental testing of prototype antennas, Final Report

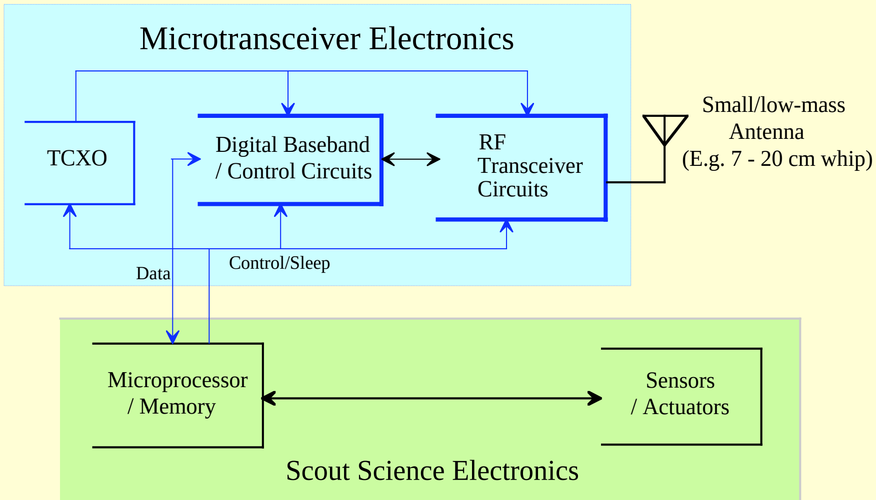
# *UHF/X-band Proximity Link Antenna*
# Significant Accomplishments and Current Status

- *Dual frequency UHF/X-Band planar antenna breadboarded and measured. Met or exceeded all specifications.*



| | Goal | Measured |
|---|---|---|
| **Gain** | >15dBic | >15.26dBic |
| **Sidelobes** | >10dB from peak | >11.9dB |
| **Axial Ratio** | <2dB peak | <1.4dB peak |
| | <4dB within BW | <2.8dB within BW |
| **Beamwidth** | no spec. | 27 deg |
| **VSWR** | <1.5:1 | <1.36:1 |

## 8. Mars Proximity Micro-Transceiver (Increase $P_T$ for a given size, mass, power and/or cost)




## Objectives:

- Develop a highly-miniaturized, extremely low-mass, low-power UHF transceiver module for aerobots, microrovers, penetrators and small network landers.
- Provide interoperability with communications infrastructure currently being developed, including the Electra UHF Transceiver on Mars Reconnaissance Orbiter.
- Produce a working prototype to TRL-6, targeting operation to –100C and 100k-Rad through temperature compensated analog/RF design and use of space-qualified rad-hard digital cell library in Silicon-on-Sapphire.

**PI:** **Bill Kuhn[1]**
Phone: (785) 532-4649
Email: wkuhn@ksu.edu
**Co-Is:** **Norm Lay[2], Edwin Grigorian[2], Dan Nobbe[3]**
Phone: (818) 393-4880, (818) 354-8579, (847) 934-2021
Email: norman.lay@jpl.nasa.gov, edwin.grigorian@jpl.nasa.gov, dnobbe@psemi.com

**Participating Organizations:**
Kansas State University[1], JPL[2], Peregrine Semiconductor[3]

**Facilities:**

K-State: Communication Circuits Laboratory
JPL: Communications Systems and Research Section Test Laboratories

## Key Milestones:

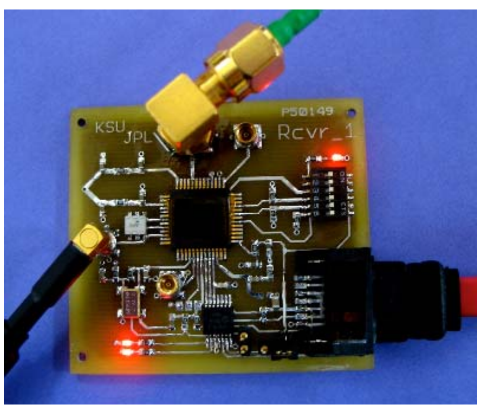
**FY05** TCXO/filtering temperature issues assessed; rad-hard cell libraries acquired; transceiver architecture and interfaces defined; digital baseband state machines defined, initial sub-circuit blocks designed;

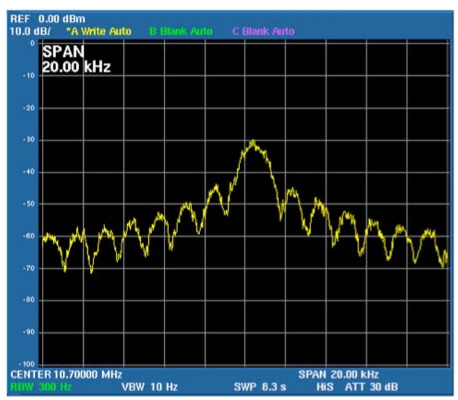
**FY06** Initial transmitter and receiver circuits complete and tested to temperature; Prox-one state machine coded and tested;

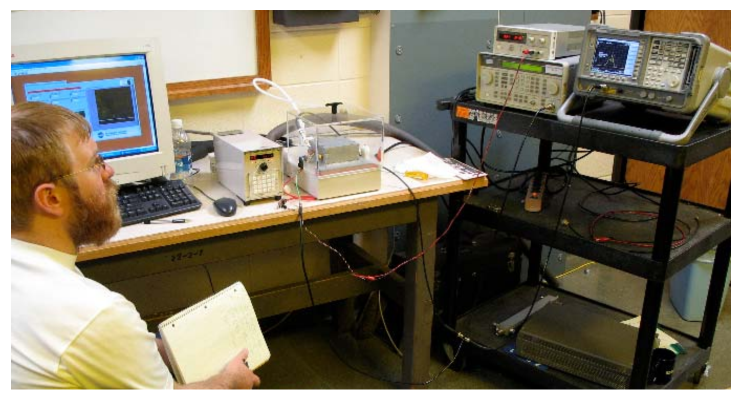
**FY07** Demonstration of full transceiver over temperature.

# *Mars Proximity Micro-Transceiver*
# Significant Accomplishments and Current Status

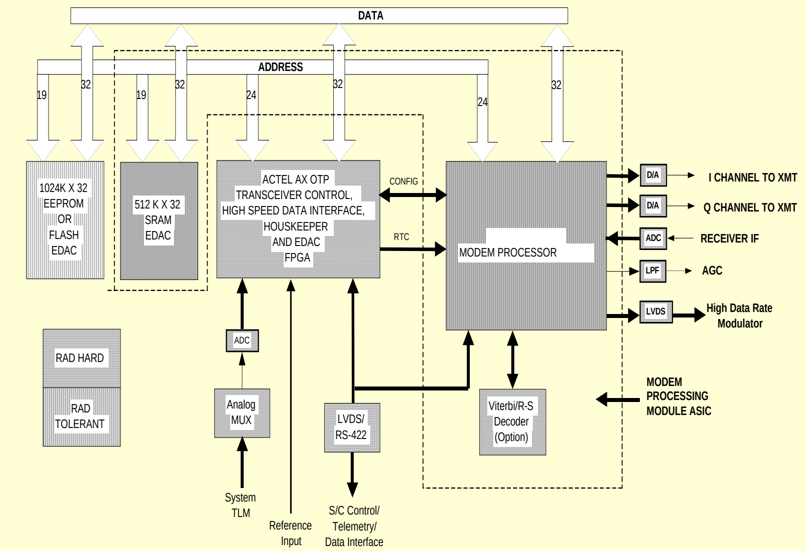
- *Acquired rad-hard libraries.*
- *Assessed temperature impacts on frequency-control/filtering.*
- *Digital baseband state diagrams defined.*
- *Receiver architecture and analog/digital interfaces defined.*
- *First prototypes of RFIC receiver and transmitter circuits fabricated and tested*
- *Digital receiver algorithms coded/tested*
- *1 Watt Power amplifier RFIC prototype expected back from foundry next month*



## *9. Reprogrammable Transceiver Modem* (Increase $P_T$ for a given size, mass, power and/or cost)




## Objective:

- Develop a Reprogrammable Transceiver Modem Processor ASIC that incorporates microcontroller, memory, HDL algorithms from the Electra Lite and the CMCEC's Advanced Reconfigurable Digital Receiver with the goal of reducing the modem mass and power by 50%.

**PI:** **Joseph Fieler**
Phone: 513-573-6219
Email: joe.fieler@L-3com.com

**Co-I:** **Tom Jedrey**
Phone: 818.354.5187
Email: tom.jedrey@jpl.nasa.gov

**Participating Organizations:** CMC Electronics Cincinnati and JPL

**Facilities:** CMC Electronics Cincinnati

## Key Milestones:

**FY05** Develop System Requirements, System Concept Design and ASIC interfaces

Incorporate and Modify ELITE Verilog DSP physical layer algorithms into ASIC

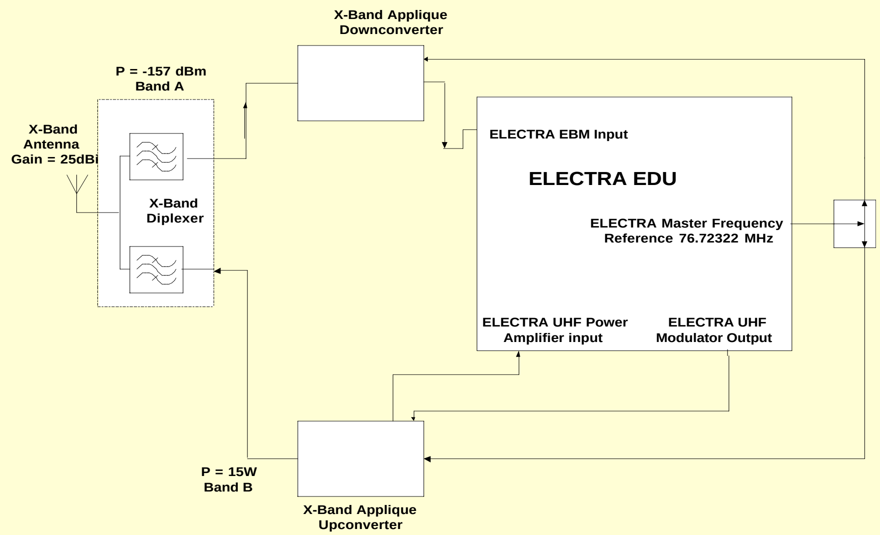
**FY06** Incorporate Processor and Memory into ASIC.

Develop System Level Test Vector and Perform Functional Simulation and Timing Analysis. Final Documentation

# *Reprogrammable Transceiver Modem*
# Significant Accomplishments and Current Status

- *Completed and published joint L-3 Communications/JPL Requirements Document*
  - *Based on requirements document for Electra-Lite*
- *System Concept Design*
  - *Developed detailed concept of system architecture*
- *Started System Architecture Design*
  - *Reviewed JPL Electra-Lite schematics and HDL*
  - *Integrating Electra-Lite JPL into ASIC architecture*
  - *Electra-Lite signals routed external of the Baseband Processing Module (BPM) will translate to ASIC I/O signals*
  - *C&DH, IF input, discrete commands, etc.*
  - *Interconnects between the two FPGAs will be maintained inside the ASIC*
- *VHDL SPARC core uses the Advanced Microcontroller Bus Architecture (AMBA)*
  - *Allows for modular system design*
  - *Designed specifically for synthesized systems*
- *Currently focused on the modem processor FPGA*

## *10. X-Band Appliqué for ELECTRA* (Increase the Carrier Frequency)




## Objectives:

- Develop a breadboard X-Band transceiver appliqué compatible with Electra. Testing will be accomplished by interfacing the appliqué with an Electra EDU.
- Phase 1 will concentrate on the receive/down-converter section.
- Phase 2 will concentrate on the up-converter/solid state power amplifier section.

**PI: Rick Hunter**
Phone: 513-573-6263
Email: rhunter@cmccinci.com

Co-I: **Rebecca Walters**
Phone: 303-939-4490
Email: rwalter@ball.com

**Participating Organizations:**

CMC Electronics Cincinnati, Ball Aerospace

**Facilities:** Cincinnati Electronics, Mason, Ohio

## Key Milestones:

**FY05** Define System Requirements, design and breadboard X-Band LNA, breadboard Phase Locked Dielectric Resonator Stabilized Oscillators, breadboard 1$^{st}$ stage of the UHF IF chain.

**FY06** Test Breadboard Downconverter with Electra EDU. Design and breadboard the X-Band Upconverter (includes RF switch, Solid State X-Band Power Amplifier, and upconverter PDRO). Test Breadboard Upconverter with Electra EDU.

# *X-Band Appliqué for ELECTRA*
# Significant Accomplishments and Current Status

- *Developed Downconverter and Upconverter Requirements*
- *Performed System Analysis and Detailed RF Design Simulations*
- *Designed, built and tested the Low Noise Amplifier*
- *Designed, built and tested the input and output RF and IF filters*
- *Designed, built and tested the Voltage-Controlled Dielectric Resonator Oscillator*
- *Design, built and tested VCDRO Buffer Amplifier Design and Test Power Sampler*
- *Designed, built and tested Phase Lock Loop*
- *Designed, built and tested IF Amplifiers*
- *Fabricated and Integrated the Downconverter Brassboard*
- *Designed, built and tested the RF Switch for the Front End*
- *Designed, built and tested the Solid-State Power Amplifier*
- *Final integration in progress*

# Performance Metrics

| Technology | Task | Parameter | Now | End of Task |
|---|---|---|---|---|
| Coding/Protocols | 1. Coding for High Data Rate Links | Decoder speed, data rate | (7,1/2) + RS = 2 Mbps | LDPC + ARQ = 5 Mbps |
| | 2. Autonomous Radio for Proximity Links | Link Margin | > 3 dB | ~ 1 dB (i.e. >+2 dB data rate) |
| | 3. Adaptive Data-Rates for ELECTRA | Data return per Orbiter Pass (MTO used as example) | <300 Mbits | 520 Mbits |
| Optical Comm | 4. Large Fresnel Lenses as Ground Receivers | 5-m receiver, cost | Photon Collector = $30 M | Fresnel Lens = $5 M |
| Antennas | 5. X-band Agile Beam Transmitter | Proximity link, antenna gain | Omni < 2 dBi | Phased Array ~ 20 dBi |
| | 6. Fast & Accurate EM Modeling | SC EM evaluation, computer | = 1 Cray | = 1 desktop |
| | 7. UHF/X-band Proximity Link Antennas | Antenna gimbal power, weight | ~ 18 W, 8 Kg | ~ 9 W, 4 Kg |
| Transceivers | 8. Mars Proximity Microtransceiver | TX/RX Power, volume, weight | ~ 50 W, 1500 cm$^3$, 2 Kg (Electra) | ~ 3 W, 18 cm$^3$, 50 g (but less capable) |
| | 9. Reprogrammable Transceiver Modem | Replace modem FPGA with ASIC, power, weight | ~ 3 W, 200 g | ~ 0.3 W, 50 g |
| | 10. X-band Applique for ELECTRA | X-band, Proximity TX/RX capability | Need SDST | Use ELECTRA |

# Mission Relevancy

| Telecommunications and Tracking Tasks | Relevancy (H/M/L) | Phoenix (2007) | MSL (2009) | Telecom /Science Orbiter | Scout | AFL | MID Rovers | Deep Drill | Current TRL | EOT* TRL (Year) |
|---|---|---|---|---|---|---|---|---|---|---|
| 1. Coding for High Data-Rate Links | H | | | ✓ | ✓ | ✓ | ✓ | ✓ | 5 | 6 (2007) |
| 2. Autonomous Radio for Proximity Links | H | | | ✓ | ✓ | ✓ | ✓ | ✓ | 4 | 6 (2007) |
| 3. ELECTRA Adaptive Data-Rates | H | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | 5 | 6 (2006) |
| 4. Fresnel Lenses Ground Receivers | L | | | | | | | | 4 | 6 (2007) |
| 5. X-band Agile Beam Transmitter | M | | | ✓ | ✓ | ✓ | ✓ | ✓ | 3 | 4 (2007) |
| 6. Fast Accurate EM Modeling | M | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | 3 | 4 (2006) |
| 7. UHF/X-band Proximity Link Antenna | H | | ✓ | ✓ | | ✓ | | | 4 | 5 (2007) |
| 8. Mars Proximity Microtransceiver | H | | | ✓ | ✓ | ✓ | ✓ | ✓ | 4 | 6 (2007) |
| 9. Reprogrammable Transceiver Modem | M | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | 3 | 4 (2006) |
| 10. X-band Applique for ELECTRA | H | | ✓ | ✓ | | ✓ | | ✓ | 4 | 5 (2006) |

* EOT – End of Task

# Conclusions

- 10 tasks of the MTP *Communications and Tracking* Technology Development Program have been presented
- Objective: Increase the aggregate data return from future Mars missions
- Approach: Develop technologies that increase the possible communications data rate for a given size, mass, power and cost.
- Tasks will result in TRL 5-6 technologies by 2007
- Appropriate infusion opportunities are being actively pursued